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Manifestation of the upper Hubbard band in conductivity of 2D p-GaAs-AlGaAs structures

N. V. Agrinskaya, Yu. L. Ivanov, V. M. Ustinov and D. A. Poloskin
Ioffe Physico-Technical Institute, St Petersburg, Russia

A significant increase to studies of conductivity in 2D structures in recent years was mostly related to experimental observation of metallic-type conductivity in Si MOSFETs and GaAs/AlGaAs heterostructures [1, 2]. Since the scaling theory of localization predicts a dielectric behavior at $T \to 0$ for any 2D structure such an observation was of principal importance. Although a lot of possible explanations of this behavior was suggested (see e.g. [3, 4]) until now no unique mechanism capable to explain all experimental features was evidenced. An attempt to attack this problem was in particular undertaken in our paper [5] where we assumed that the behavior observed is dominated by a contribution of the upper Hubbard band corresponding to the bandtail of localized states. However an absence of independent information concerning the localized states in the 2D structures mentioned above does not allow a direct comparison of theoretical predictions with experimental data.

Correspondingly, a possibility to study transport in the upper Hubbard band in some model system with a clear picture of localized states is to our opinion of undoubted interest. One expects that for 3D case an observation of the contribution of the upper Hubbard band is a complicated task since according to theoretical calculations the energy of doubly occupied shallow impurity state of donor (D^-) or acceptor (A^+) type is too small ($E_- = 0.055E_0$, where E_0 is the binding energy of the isolated impurity); correspondingly, the conductivity over the upper Hubbard band was considered to be unimportant with respect to the contribution of the standard conductivity band. Note that according to our previous studies the signiture of the upper Hubbard band can be traced in hopping magnetoresistance of different semiconducting materials while the extracted values of the corresponding Hubbard energy have appeared to be much less than theoretical estimates.

An encouraging situation in this concern corresponds to 2D systems with selective doping where the concentration of electrons in a well can be varied in a controlled way and, cosequently, one can control a relation between single-occupied and doubly-occupied localized states. Then, in the narrow enough wells (when the spatial scale of the site wave function becomes to be comparable to the well width) the energies E_- and E_0 are enhanced. It is expected that such an enhancement of the binding energy is more pronounced for D^- state because of the larger value of localization radius. Thus a situation is possible when the energy of D^- state is already lowered while the energy of D_0 state is not changed significantly which leads to a decrease of the Hubbard energy. This latter fact improves the possibilities to study the contribution of the D-band.

We have chosen the system GaAs/AlGaAs with the well width $d \sim 15$ nm which was doped by acceptor impurity Be having a localization radius (2 nm) much smaller than d. By a selective doping of the well regions and the barrier regions we have reached a situation when the upper Hubbard band has been occupied in the equilibrium, the conductivity being over its states. The experiments have shown that the binding energy of A^+ state increases significantly for the wells with $d = 15$ nm with respect to the bulk case. We have estimated

the radius of this state independently from an analysis of temperature behavior of hopping conductivity.

1. Experiment

The structures to be studied were MBE-grown on semiinsulating substrates GaAs(100) with a help of Riber 32P equipment supplied by solid sourses Ga, Al, As and Be. The growth took place in As-enreached conditions at the substrate temperature 580 °C, the growth rate being 10 nm/min. The structures contain 10 quantum wells with a width 15 nm separated by barriers AlGaAs with a thickness 15 nm. The confining layers AlGaAs were deposited before the first well and after the last one. The growth was finished by a deposition of the covering GaAs layer with a thickness 20 nm. In the both samples studied the middle region of the well (with a thickness 5 nm) was doped; in one of the samples (293) the barriers were undoped while in another sample (213) the middle region of the barriers with a width 5 nm was doped. Thus the widths of the undoped spacer layers from both sides of the barrier. We used Be as p-type dopant with a concentration 10^17 atoms/cm^3; the hole concentration measured at $T = 300$ K was equal to $8 \cdot 10^16\,\mathrm{cm}^{-3}$ and $10^{17}\,\mathrm{cm}^{-3}$ for sample 293 and 213 correspondently. The contacts were made by cintering in of sputtered Au containing 3% of Zn during 2 min at temperature 150 °C.

In Fig. 1 we showed temperature behavior of Hall coefficient for the two samples. The temperature region 50–300 K corresponds to ionization of acceptors into the valence band. The fact that the carrier transport takes place in the valence band is evidenced by rather high values of mobility — (300–500) cm^2 V/s at 300 K — and by its temperature behavior $\mu \sim T^{-3/2}$. At low temperatures the activation law of Hall coefficient is observed; at higher temperatures the slop is decreased which can be related to devastation of impurities. In particular, for the sample 293 exhibiting some compensation degree (rather probable in a view of a presence of background impurities and interface states) at low temperatures there exists a region with a slope E_a while at higher temperatures a region with a slope $E_a/2$ is exhibited. The ionization energies estimated from the slopes mentioned above appear to

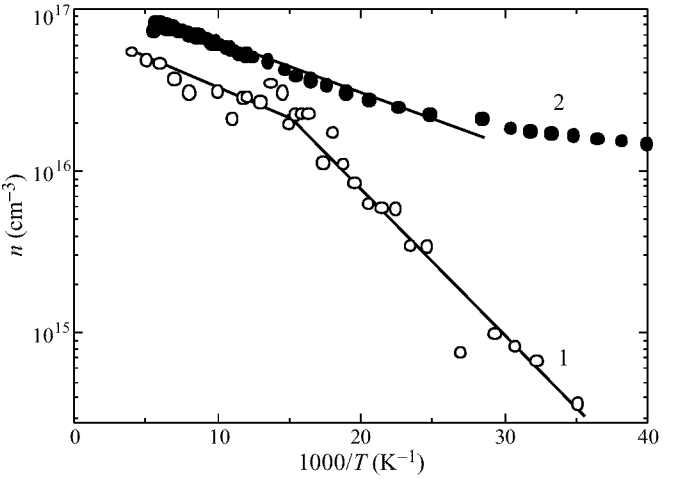

Fig. 1. Temperature behavior of carrier concentrations for the two samples calculated from Hall coeficient: 1—sample 293, 2—sample 213. The carrier concentrations were calculated as averaged over the volume with an account of the sample thickness 150 nm

be different for the two samples and are equal to 7 meV and 21 meV, respectively.

At temperatures lower than 50 K (up to 1.7 K) the temperature behavior of conductivity evidences its hopping character (Fig. 2). The slopes of $\sigma(T)$ in terms of $T^{-1/3}$ are different for the two samples.

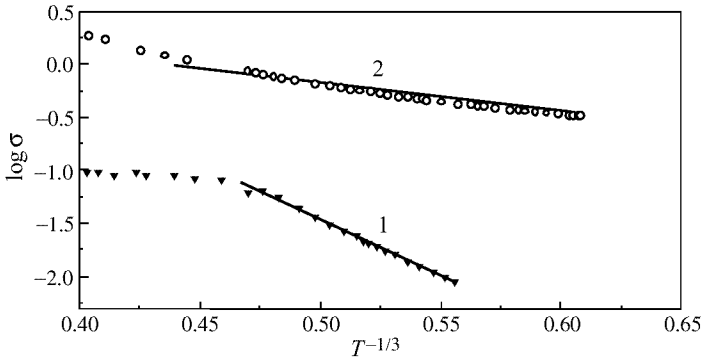

Fig. 2. Temperature behavior of conductivity for the two samples: 1—sample 293, 2—sample 213.

2. Discussion

According to the data published until now, the position of Be level in GaAs corresponds to 27 meV. Our experiment shows for the sample 293 (only GaAs layers are doped) the activation energy 20 meV. The discrepance can be ascribed to a finite width of the impurity band W which for weakly compensated sample according to theoretical prediction is

$$W = \frac{e^2}{\kappa} N^{1/3}$$

where κ is the dielectric constant, N is the impurity concentration. This estimate gives for $N = 10^{17}\,\mathrm{cm}^{-3}$ $W = 10$ meV that is the value of $W/2$ is in agreement with the difference between the ionization energy observed and the energy of the bare level. For the sample 213 (both GaAs layers and the barrier regions are doped) much lower ionization energy (7 meV) is observed. In this case the additional holes occupy the second charge state A^+ of the acceptors in GaAs layers. According to the theoretical estimates the ionization energy of the A^+ state is $0.05E_0$. The observed value is by a factor of 5 higher which we ascribe to the 2D character of the structure. Indeed, while the ground state radius a_0 is equal to 30 Å (which is much less than the well width) the radius of A^+ state is expected to be much larger ($\sim 4a_0$) and is of the order of the well width. This factor leads to a lowering of the A^+ energy and to a decrease of the Hubbard energy (by definition being a difference between energies of A_0 and A^+ centers). The indepenndent estimate of A_0 and A^+ centers radii can be obtained on the base of the analysis of low temperature conductivity corresponding to variable range hopping. Since the hopping length al low temperatures definitely exceeds the well width, we deal with 2D hopping described by the law

$$\sigma = \sigma_0 \exp\left(-\frac{T_0}{T}\right)^{1/3}$$

where T_0 is the parameter related to the density of states at the Fermi level and the localization radius:

$$T_0 = C(N_F a^2)^{-1}$$

($C = 13.8$ being a numerical coefficient). In Fig. 2 we depicted the low temperature behavior of conductivity for the two samples in terms of $T^{-1/3}$. As it is seen, the behavior corresponds to straight lines while the slopes allow to extract the values of T_0 — 103 K (sample 293) and $1.5 \cdot 10^3$ K (sample 213). If one supposes that the densities of states at the Fermi level are equal for 293 and 213 samples the square root of the ratio of these parameters gives the ratio of the radia corresponding to the two samples . The ratio of the radia of A_0 and A^+ states found in such a way is equal to 4, that is the radius of A^+ center is equal to 12 nm which is comparable with the size of the structure. Thus the experiments evidenced that the A^+ binding energy is significantly (by a factor of 5) enhanced for the wells with a width 15 nm with respect to the bulk case which is related to the fact that the radius of A^+ state is comparable to the well width.

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